

# Long and short gamma-ray bursts, and the pulsar kicks

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One of the mysteries that surround gamma-ray bursts (GRB) is the origin of two classes of events: long and short GRB<sup>1</sup>. The short GRB are similar to the first second of a long GRB<sup>2</sup>. We suggest that the short bursts are interrupted long bursts, we point out a plausible mechanism for the interruption, and we explain the observed time scales. The supernova-like central engine may contain a neutron star or a black hole surrounded by an accretion disk and jets. In the case of a neutron star, the same mechanism that is responsible for the pulsar kicks can disrupt the central engine, thus producing an interrupted, short GRB. If a black hole is produced, the absence of the kick ensures the long duration of the GRB. The time delay of the kick and the absence of the kick for a black hole are natural consequences of a model based on neutrino oscillations<sup>3</sup>.

Observational evidence suggests that gamma-ray bursts are supernova-like phenomena<sup>4</sup>. This evidence is stronger for the long GRB, which last longer than a few seconds and for which the optical afterglows have been detected. It is now established that the long GRB occur in star forming regions. The central engine is probably a sort of a supernova explosion, which is different from ordinary supernovae in that a large fraction of energy is concentrated in highly relativistic jets. On the other hand, for short GRB, the lack of optical afterglows leaves open several other possibilities. For example, neutron star and black hole mergers are probably not ruled out<sup>5</sup>.

In this *Letter* we will argue that both long and short GRB can originate from the same supernova type central engine that produces either a black hole or a neutron star, respectively. The main reason why the short bursts are shorter is that the jet, pointing originally along the line of sight, is disrupted by the same dynamical mechanism that is responsible for the “pulsar kicks”. A model for such a mechanism<sup>3</sup> based on neutrino oscillations predicts a delay on the time scale of order of a few seconds, which can naturally explain the durations of the interrupted bursts. The same kick mechanism does not act on a black hole<sup>3</sup>. Thus, if the central engine is a black hole, the jet exists and maintains its direction along the line of sight for (much) longer than a second, which results in a long GRB. We suggest, therefore, that the long GRB come from central engines containing black holes, while the short ones originate from those with neutron stars.

The pulsar kick may also be the origin of unusually high rotational velocities of pulsars at birth<sup>6</sup>. The kick is not expected to be a central force. Hence, it simultaneously kicks the pulsar and spins it up. At the time of the kick both the position and the angular momentum of the neutron star change dramatically.

Since the accretion disk and the jet are gravitationally bound to the neutron star, the pulsar kick can disrupt the jet entirely. An average pulsar velocity is 200-500 km/s, although about 15% of pulsars have velocities in excess of 1000 km/s<sup>7</sup>. The neutron star is strongly gravitationally bound to a part of the accretion disk of the size, roughly, 10 neutron star radii,  $D \sim 10R_{\text{NS}} \approx 150$  km. Therefore, it takes from 0.1 to 1 second after the kick for the neutron star to leave the central region of the accretion disk. This can either terminate the jet entirely, or can change its direction. The kick changes the angular momentum of neutron star, which affects the total angular momentum of the system and, thus, the direction of the jet. In either case, whether the jet is disrupted entirely or it is kicked off the line of sight, the kick terminates the GRB.

The two essential elements of this picture, illustrated in Fig.1, are the presence of a compact star in the central engine and the existence of a pulsar kick mechanism which acts on a neutron star within one second of the onset, and which does not act on a black hole. We will first discuss the phenomenological consequences of such a mechanism, and then we will argue that a microscopic model based on neutrino oscillations<sup>3</sup> is suitable.

This simple explanation can account for the following observational features of GRB:

- short-time variability on the millisecond time scale for all bursts
- temporal and spectral similarities between the short bursts and the first seconds of the long bursts
- lack of the optical afterglows following the short GRB
- approximate fluence-duration proportionality
- characteristic time scale of about 1 s separating the two classes of bursts
- supershort bursts

We will discuss each of these items below.

*Short-time variability* is a natural consequence of a small size of the compact star at the center of the engine. The observed gamma rays are generated in the jet by some dynamics that may involve shocks and flow irregularities. However, the millisecond time scale in the temporal profile of bursts is suggestive of a small size dynamics that modulates the jet at its origin. Causality forces one to associate the millisecond time intervals with length scales of the order of a kilometer. Hence, a compact central object is called for. In addition, the smaller the central engine, the stronger is the field of gravity in the region where the jet originates. This can help accelerate the accreting material to higher speeds before it is ejected out into the jet. Given the tight energetic constraints on the central engine, it is desirable to extract as much energy as possible in the form of a narrow jet. Therefore, the presence of a compact star in the central engine is definitely a desirable feature of the model. An improvement in temporal sensitivity of observations in the millisecond range, in combination with improved theoretical modeling, may help distinguish black holes from neutron stars by measuring short-time variability, which may be different for those two cases.

*Temporal similarities between the short and long bursts* are to be expected if the short bursts are merely the interrupted long bursts. This is strongly supported by recent observations<sup>2</sup>, which demonstrate that the first seconds of the long bursts are almost identical to the short bursts. Improved future analyses may reveal a softening of the short GRB toward the end, when the central engine is disrupted.

*The lack of optical afterglows for the short bursts* may be the consequence of a disruption of the central engine and the jet by the kick force. The

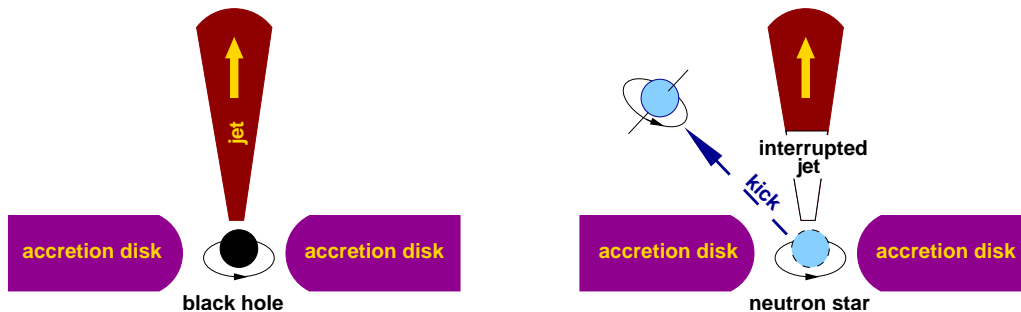


Figure 1: The central engine may contain a black hole or a neutron star. In the case of a black hole, the jet continues uninterrupted for tens of seconds. This is long GRB. In the case of a neutron star, about a second after the onset of the GRB, the pulsar kick (due to neutrinos<sup>3</sup>, or some other mechanism) displaces the neutron star and changes its angular momentum, disrupting the central engine. This produces a short, interrupted gamma-ray burst with similar characteristics to the first few seconds of a long burst<sup>2</sup>.

isotropic emission of light in a supernova is insufficient to produce an observable afterglow at large red shift. Thus, after the jet is disrupted, one does not expect an afterglow of observable luminosity. In the black hole case, the jet remains stable for the entire duration of the (long) GRB, and the same jet can be detected at a later time as an afterglow. However, an early optical afterglow for a short GRB is also possible if it results from an interaction of the interrupted jet with ambient matter.

*The approximate fluence-duration proportionality*<sup>8</sup> is also explained in our model because the short bursts are supposed to be the interrupted long ones. In the absence of the interruption by the kick force, the short burst would have continued and would have produced the total luminosity typical of a long burst. The disruption of the jet ends the emission of energy in the direction of the observer.

The fluence – duration power law is softer for the short GRB than it is for the long ones<sup>8</sup>. This observation fits in our model because the black holes can make more powerful engines than the neutron stars. This is because the black holes can have a larger mass and a smaller size simultaneously.

*The characteristic time scale of order 1 s* arises naturally in a model that explains the pulsar kicks by neutrino oscillations<sup>3</sup>. There are actually two viable mechanisms, based on the resonant<sup>9</sup> and non-resonant<sup>3</sup> oscillations, respectively. The unknown neutrino parameters determine which of

the two (mutually exclusive) mechanisms is a work. In the case of resonant oscillations, the force is applied from the onset of the neutron star cooling, with no delay. However, for different neutrino parameters, the off-resonant mechanism<sup>3</sup> is operative, and the kick starts only after some time  $\tau \sim 1\text{ s}$ , which is a natural time scale to explain the difference between the short and the long GRB. This pulsar kick mechanism requires that a singlet fermion, having a keV mass and mixed with the electron neutrino, be present in the neutrino spectrum. Serendipitously, the same singlet neutrino can be the dark matter in the universe<sup>3, 10</sup>. The kick begins after the effective matter potential for neutrino oscillations is reduced by neutrino conversions. The time it takes<sup>3</sup> before the start of the kick is estimated to be

$$\begin{aligned}\tau &\simeq \frac{4\sqrt{2}\pi^2 m_n}{G_F^3 \rho} \frac{(V_m^{(0)})^3}{(\Delta m^2)^2 \sin^2 2\theta} \frac{1}{\mu^3} \\ &\sim 1\text{ s} \left( \frac{10^{-8}}{\sin^2 2\theta} \right) \left( \frac{50\text{ MeV}}{\mu} \right)^3 \left( \frac{10\text{ keV}^2}{\Delta m^2} \right)^2,\end{aligned}\tag{1}$$

where  $\rho$  and  $\mu$  are the density and the electron chemical potential inside the neutron star,  $\Delta m^2$  is the difference in neutrino masses squared,  $\theta$  is the singlet-active neutrino mixing angle, and  $V_m^{(0)} \sim 0.1\text{ eV}$  is the initial value of the matter potential. The mixing  $\sin^2 2\theta \sim 10^{-11} - 10^{-7}$  for a  $1 - 10\text{ keV}$  singlet neutrino is consistent with dark matter<sup>10</sup>. Clearly, the one-second time scale is a natural prediction of this mechanism.

Even if there is no delay, and the pulsar kick occurs at the time of the formation of the jet, the observed pulsar velocities of the order of a few hundred km/s can explain the  $\sim 1\text{ s}$  time scale. Indeed, it may be necessary to remove the pulsar at least a distance  $D \sim 10R_{NS} \sim 150\text{ km}$  away from its original position to disrupt the jet. Thus, the jet may remain intact for the time  $\sim D/v$ , where  $v$  is the pulsar velocity. The range of time delays that arise this way is determined by the distribution of pulsar velocities<sup>7</sup>. Since most pulsars move faster than  $100\text{ km/s}$ , we do not expect a burst that lasts much longer than a second as long as the engine is powered by a neutron star.

*Supershort bursts.* Gamma-ray bursts with a very short duration  $\tau < 0.1$  second are sometimes considered as a separate class of GRB<sup>11</sup>. It is possible that such short bursts appear because a jet, which was not pointing at Earth initially, changes its direction and quickly passes through the line of sight when the neutron star is kicked. Alternatively, the supershort bursts may

correspond to the neutron stars with the highest velocities, which move out of the central region in much less than a second.

Our model can, in principle, relate the numbers of the long and the short gamma-ray bursts to the birth rates of black holes and neutron stars, respectively. Simple estimates of the integrated galactic birth rates for compact stars<sup>12</sup> suggest that neutron stars are born at two or three times the rate of black holes. However, neutron stars and black holes are born from progenitors of different masses. This may affect the angular size of the jet, the brightness, and, ultimately, the detectability of the GRB. Therefore, we cannot relate the numbers of the short and long GRB directly to the birth rates of compact objects.

Our model agrees with non-observation of *late* optical afterglows for short GRB. If such afterglows will be observed in the future, interpretation of short GRB as interrupted jets will become less convincing.

To summarize, we have proposed that the long GRB originate from supernova-like explosions that result in a formation of a black hole, while the short GRB originate in the same way, except a neutron star forms instead of a black hole. The neutron stars undergo the same dynamical impacts that cause the pulsar kicks. As a result, the momentum and the angular momentum of the neutron star and of the gravitationally bound accretion disk change dramatically. This impact either disrupts the jet altogether or changes its direction away from the line of sight. Central engines that contain neutron stars can, therefore, produce short GRB. At the same time, a central engine with a black hole, which is not a subject to the kick force (at least as long as the pulsar kick is due to neutrino oscillations), would produce a long GRB. At least one plausible model for the pulsar kick mechanism<sup>3</sup> predicts that the kick force would be delayed by a period of time of order one second. However, regardless of the microscopic mechanism, since most pulsars have velocities in excess of 100 km/s<sup>7</sup>, the pulsar kick should remove the neutron star from the central region within about a second, which should destabilize the jet. Our model can be generalized to include any kick mechanism that acts on a neutron star but does not act on a black hole. This can be the explanation for the time separation between the two populations of bursts.

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